CP violating asymmetries induced by supersymmetry

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Outline

Baryon asymmetry of the universe

- Exists much more baryonic matter than anti-matter
- Standard Model (SM) *cannot* explain baryon asymmetry of the universe!
- Evidence from acoustic peaks (early universe baryon-photon plasma oscillations) deduced from Cosmic Microwave Background measurements

Baryon-to-photon ratio

$$\eta \equiv \frac{n_B}{s} \equiv \frac{n_b - n_{\bar{b}}}{s} = (6.1^{+0.3}_{-0.2}) \times 10^{-10}$$

s … entropy density (roughly photon density)
$n_b(n_{\bar{b}})$ … number densities of baryons (anti-baryons)

Baryogenesis

Problem

How obtains η this small value from initial condition $\eta = 0$?

Criteria of a solution

Three necessary conditions for baryogenesis:
Sakharov requirements

1. Baryon number violation
2. Departure from thermal equilibrium
3. Charge (C) and *Charge-Parity (CP) violation*

SM can meet Sakharov criteria but baryon asymmetry is *too small*!

Possible solution

- Supersymmetric extensions of SM can contain new sources of CP violation
- Lead to increase and thus possible explanation of baryon asymmetry
- Special case: Minimal Supersymmetric Standard Model (MSSM) introduces new parameters
- If some parameters are chosen *complex*, radiative corrections at one-loop can lead to *new CP violating asymmetries*

Supersymmetry (SUSY)

Main idea

Symmetry between bosons and fermions

- Superpartner: same quantum numbers and mass but different spin
- Simplest case: superpartner for every particle of the SM
- Until now no superpartners found
  - Have a high mass
  - Explainable with spontaneous breaking of supersymmetry

Particle content of the MSSM

- All particles obtain a superpartner
- Particle and superpartner form *supermultiplets*
- More than one Higgs particle
- Naming convention
  - Prefix 's' for spin = 0 superpartner (sleptons, squarks, ...)
  - suffix '-ino' for spin = $\frac{1}{2}$ superpartner (gluino, Higgsinos ...)
- Superpartner mix because of electroweak symmetry breaking

Particle content of the MSSM
Chiral supermultiplets

Names		Spin 0	Spin 1/2	$SU(3)_C$, $SU(2)_L$, $U(1)_Y$
squarks, quarks	$\tilde{Q}$	$(\widetilde{u}_L \;\; \widetilde{d}_L)$	$(u_L \;\; d_L)$	$(\,\mathbf{3},\ \mathbf{2}\,,\ \frac{1}{6})$
($\times$3 families)	$\overline{u}$	$\widetilde{u}_R^*$	$u_R^\dagger$	$(\,\overline{\mathbf{3}},\ \mathbf{1},\ -\frac{2}{3})$
	$\overline{d}$	$\widetilde{d}_R^*$	$d_R^\dagger$	$(\,\overline{\mathbf{3}},\ \mathbf{1},\ \frac{1}{3})$
sleptons, leptons	$\tilde{L}$	$(\widetilde{\nu} \;\; \widetilde{e}_L)$	$(\nu \;\; e_L)$	$(\,\mathbf{1},\ \mathbf{2}\,,\ -\frac{1}{2})$
($\times$3 families)	$\overline{e}$	$\widetilde{e}_R^*$	$e_R^\dagger$	$(\,\mathbf{1},\ \mathbf{1},\ 1)$
Higgs, Higgsinos	H_u	$(H_2^1 \;\; H_2^2)$	$(\widetilde{H}_2^1 \;\; \widetilde{H}_2^2)$	$(\,\mathbf{1},\ \mathbf{2}\,,\ +\frac{1}{2})$
	H_d	$(H_1^1 \;\; H_1^2)$	$(\widetilde{H}_1^1 \;\; \widetilde{H}_1^2)$	$(\,\mathbf{1},\ \mathbf{2}\,,\ -\frac{1}{2})$

Spin-0 fields are complex scalars
Spin-$1/2$ fields are left-handed two-component Weyl fermions

Particle content of the MSSM

Gauge supermultiplets & mixing

Names	Spin 1/2	Spin 1	$SU(3)_C,\ SU(2)_L,\ U(1)_Y$
gluino, gluon	$\widetilde{g}$	g	$(\mathbf{8},\ \mathbf{1},\ 0)$
winos, W bosons	$\widetilde{\lambda}^{\pm}\quad\widetilde{\lambda}^{3}$	$W^{\pm}\quad W^{0}$	$(\mathbf{1},\ \mathbf{3},\ 0)$
bino, B boson	$\widetilde{\lambda}'$	B^{0}	$(\mathbf{1},\ \mathbf{1},\ 0)$

- Remember:
  Interaction eigenstates no longer mass eigenstates (physical particles)!
- Needs to consider mixing of interaction eigenstates to mass eigenstates

Particle content of the MSSM

Mixing of eigenstates

Names	Spin	P_R	Gauge Eigenstates	Mass Eigenstates
Higgs bosons	0	$+1$	H_2^0 H_1^0 H_2^+ H_1^-	h^0 H^0 A^0 $H^\pm$
squarks	0	-1	$\widetilde{u}_L$ $\widetilde{u}_R$ $\widetilde{d}_L$ $\widetilde{d}_R$ $\widetilde{c}_L$ $\widetilde{c}_R$ $\widetilde{s}_L$ $\widetilde{s}_R$ $\widetilde{t}_L$ $\widetilde{t}_R$ $\widetilde{b}_L$ $\widetilde{b}_R$	$\widetilde{u}_1$ $\widetilde{u}_2$ $\widetilde{d}_1$ $\widetilde{d}_2$ $\widetilde{c}_1$ $\widetilde{c}_2$ $\widetilde{s}_1$ $\widetilde{s}_2$ $\widetilde{t}_1$ $\widetilde{t}_2$ $\widetilde{b}_1$ $\widetilde{b}_2$
sleptons	0	-1	$\widetilde{e}_L$ $\widetilde{e}_R$ $\widetilde{\nu}_e$ $\widetilde{\mu}_L$ $\widetilde{\mu}_R$ $\widetilde{\nu}_\mu$ $\widetilde{\tau}_L$ $\widetilde{\tau}_R$ $\widetilde{\nu}_\tau$	$\widetilde{e}_1$ $\widetilde{e}_2$ $\widetilde{\nu}_e$ $\widetilde{\mu}_1$ $\widetilde{\mu}_2$ $\widetilde{\nu}_\mu$ $\widetilde{\tau}_1$ $\widetilde{\tau}_2$ $\widetilde{\nu}_\tau$
neutralinos	$1/2$	-1	$\widetilde{\lambda}'$ $\widetilde{\lambda}^3$ $\widetilde{H}_2^2$ $\widetilde{H}_1^1$	$\widetilde{\chi}_1^0$ $\widetilde{\chi}_2^0$ $\widetilde{\chi}_3^0$ $\widetilde{\chi}_4^0$
charginos	$1/2$	-1	$\widetilde{\lambda}^\pm$ $\widetilde{H}_2^1$ $\widetilde{H}_1^2$	$\widetilde{\chi}_1^\pm$ $\widetilde{\chi}_2^\pm$
gluino	$1/2$	-1	$\widetilde{g}$	$\widetilde{g}$

Definitions

- C transformation changes sign of charge, changes particle to its anti-particle
- P transformation changes sign of coordinate system, turns right-handed coordinate system into a left-handed one or vice versa $P: \ \psi(t,\vec{x}) \rightarrow \psi(t,-\vec{x})$
- CP transformation applied to Lagrangian changes
  - Signs of momentums and charges
  - Left- and right-handed parts
  - *Conjugates coupling matrices*
- If coupling matrices are *complex*, CP violation can occur!

Definitions

- Decay rate asymmetry $\delta^{CP} = \frac{\Gamma^+ - \Gamma^-}{\Gamma^+ + \Gamma^-}$
- $\Gamma^{+,-}$ decay rate of a process (regular, CP transformed)
- Special case: $\Gamma^+ = \Gamma(\tilde{t}_i \to b\,\tilde{\chi}_k^+)$, $\Gamma^- = \Gamma(\tilde{t}_i^* \to \bar{b}\,\tilde{\chi}_k^{+c})$
- Branching ratio $BR = \frac{\Gamma}{\Gamma_{\text{total}}}$
- $\delta^{CP} \times BR$ probability how often certain decay is CP violated (compared to rest)

Decay rate asymmetry δ^{CP}

Decay rate asymmetry δ^{CP} is $\neq 0$ only if

1. including radiative corrections with at least one-loop
(both CP transformation and calculating adjoint matrix $\mathcal{M}^\dagger$ (in $\Gamma \propto \sum_s \mathcal{M}^\dagger \mathcal{M}$) conjugate tree-level couplings -> at tree-level net effect zero)
2. coupling between particles complex
(due to complex MSSM parameters)
(CP transformation conjugates tree-level couplings)
3. at least a second decay channel open
(i.e. in addition to $\tilde{t}_i \rightarrow b\,\tilde{\chi}_k^+$ another like $\tilde{t}_i \rightarrow t\,\tilde{g}$)
(From CPT Theorem: only total decay width Γ_{total} CP invariant, but not necessarily partial decay widths!)

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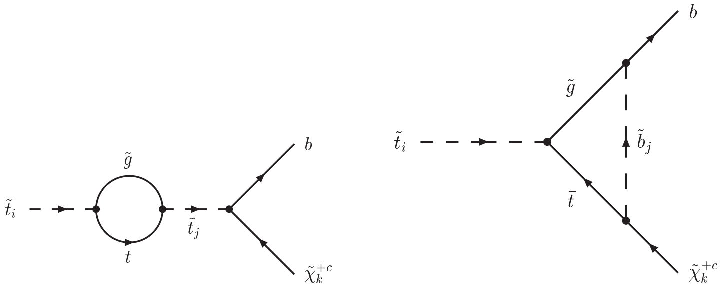
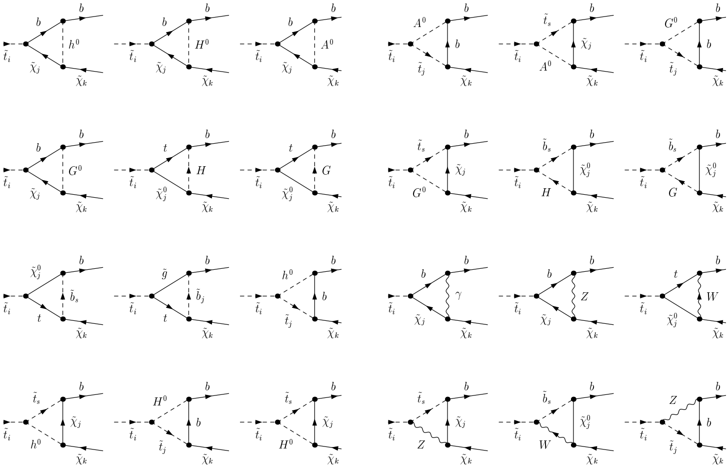
Most important contributions (expected)

All gluino contributions

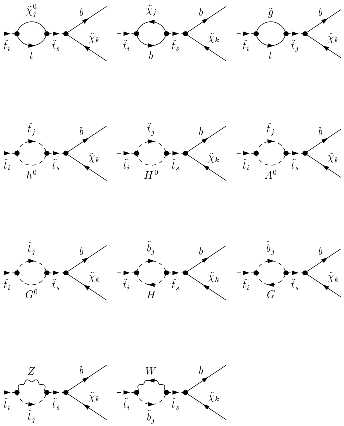


- Gluino $\tilde{g}$ couples like gluon g with strong interaction force
- If decay $\tilde{t}_i \to t\,\tilde{g}$ kinematically possible, these contributions should dominate over all others

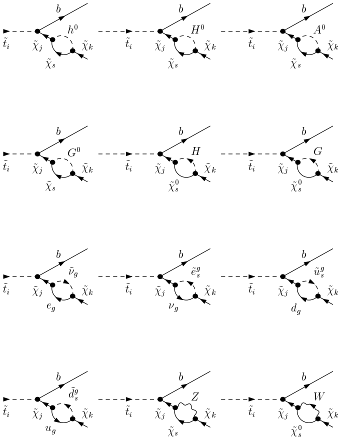
All vertex contributions



All stop-selfenergy contributions



All chargino-selfenergy contributions



Calculation

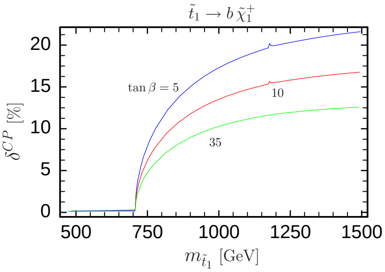
- Derived most important contributions analytically and numerically by myself
  (including derivation of mass matrices, couplings, generic structures etc)
- Calculation of full one-loop corrections with FeynArts/FormCalc/LoopTools
  (successfully checked with own computations)
- Input parameters of SM and MSSM for a typical scenario
- Complex parameters can violate experimental limit of electric dipole moment of electron
  - Checked automatically with self-written routine

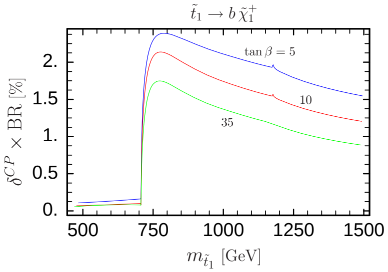
Some input parameters of SM and MSSM

- Coupling of strong interaction force α_s is taken running in dimensional reduction regularization scheme $\overline{DR}$, renormalized at scale of decaying particle (SPA convention)
- Gluino mass $m_{\tilde{g}}$ calculated from α_s via GUT relations
- Yukawa couplings of third generation (s)quarks (h_t, h_b) are taken running
- SUSY breaking mass parameters $M_{\tilde{Q}}$, $M_{\tilde{u}}$, $M_{\tilde{d}}$, $M_{\tilde{L}}$ and $M_{\tilde{e}}$ set equal in all generations
- Trilinear breaking parameters of 1st and 2nd generation set to zero $(A_{u,d,e} = A_{c,s,\mu} = 0)$
- We further simplify and set $|M_1| = M_2/2$ (GUT relation), $M_{\tilde{Q}} = M_{\tilde{u}} = M_{\tilde{d}}$, $M_{\tilde{L}} = M_{\tilde{e}}$, $|A_t| = |A_b| = |A_\tau|$ and $\varphi_{A_t} = \varphi_{A_b} = \varphi_{A_\tau}$
- Due to stringent experimental constraints, we set $\varphi_\mu = 0$ (phase of Higgsino mass) and focus just on phase of A_f (the phase of SUSY breaking gaugino mass M_1 is negligible in our case)

Some numerical results

$\tilde{t}_1 \to b\,\tilde{\chi}_1^+$ (All contributions)

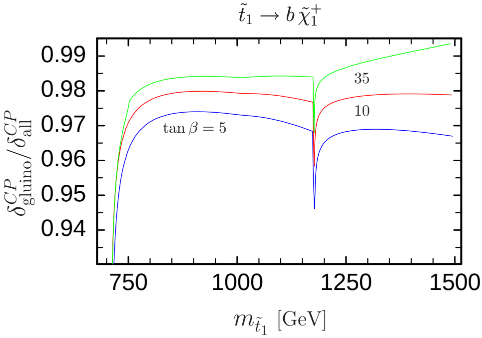




- Actually vary input parameter $M_{\tilde{Q}}$ (SUSY breaking mass) from 500 to 1500 GeV but show output parameter $m_{\tilde{t}_1}$ for convenience
- $\tan\beta$ is ratio of the two VEVs of Higgs fields
- Threshold of decay $\tilde{t}_1 \to t\,\tilde{g}$ at $m_{\tilde{t}_1} \sim 708$ GeV
- Dominance of gluino contributions over all insignificant others
- $\delta^{CP}_{\max} \sim 22\,\%$, $(\delta^{CP} \times BR)_{\max} \sim 2.4\,\%$

Some numerical results

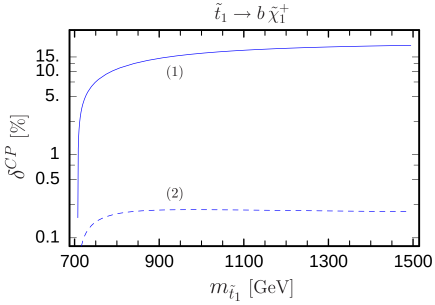
$\tilde{t}_1 \to b\,\tilde{\chi}_1^+$ (Gluino-to-all ratio)



- After threshold at $m_{\tilde{t}_1} \sim 708$ GeV gluino processes account for $\sim 98\,\%$ of all processes
- Kink at $m_{\tilde{t}_1} \sim 1175$ GeV comes from threshold of $\tilde{t}_1 \to t\,\tilde{\chi}_3^0$

Some numerical results

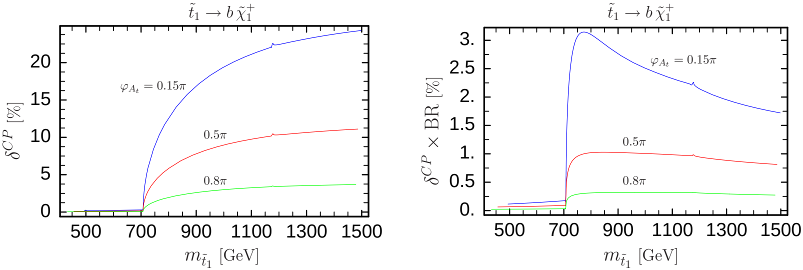
$\tilde{t}_1 \to b\,\tilde{\chi}_1^+$ (Comparison of gluino contributions)



- (1) Gluino in selfenergy-loop,
  (2) Gluino in vertex correction
- Contrary to expectation only *one* gluino contribution dominates!
- Reason lies in coupling $\tilde{b}_j - t - \tilde{\chi}_1^+$ embedded in vertex correction, however no simple explanation possible

Some numerical results

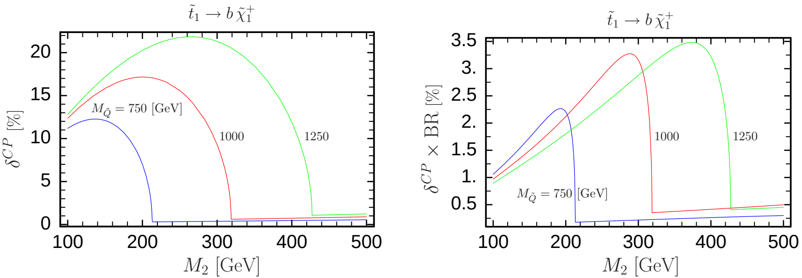
$\tilde{t}_1 \to b\,\tilde{\chi}_1^+$ (All contributions)



- Complex phase of breaking parameter A_t highly influences δ^{CP} (only source of CP violation in our scenario)
- Overall maximum of scenario: $\delta^{CP}_{\text{max}} \sim 24\,\%$

Some numerical results

$\tilde{t}_1 \to b\,\tilde{\chi}_1^+$ (All contributions)



- Closure of dominating decay channel $\tilde{t}_1 \to t\,\tilde{g}$, because SUSY breaking gaugino mass M_2 is related to gluino mass $m_{\tilde{g}}$
- The higher mass $M_{\tilde{Q}}$ ($m_{\tilde{t}_1}$), the later this closure happens
- Overall maximum of scenario: $\delta^{CP} \times BR \sim 3.5\,\%$

Summary

- Baryogenesis needs CP violation exceeding the one in SM
- Minimal Supersymmetric Standard Model (MSSM) with complex parameters leads to new CP violation
- One-loop corrections to $\tilde{t}_i \to b\,\tilde{\chi}_k^+$ leads to CP violating decay rate asymmetry δ^{CP}
- Detailed numerical analysis of δ^{CP} and $\delta^{CP} \times BR$
- δ^{CP} rises up to $\sim 24\,\%$, $\delta^{CP} \times BR$ up to $\sim 3.5\,\%$
- Asymmetry δ^{CP} will be measurable at LHC